Where are the sources of the near infrared background?

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ABSTRACT
The observed near infrared background excess over light from known galaxies is commonly ascribed to redshifted radiation from early, very massive, PopIII stars. We show here that this interpretation must be discarded as it largely overpredicts the number of J-dropouts and Lyα emitters in ultra deep field searches. Independently of the detailed physics of Lyα line emission, J-dropouts limit the background excess fraction due to PopIII sources to be (at best) $\leq 1/24$. As alternative explanations can either be rejected (e.g. miniquasars, decaying neutrinos) or appear unlikely (zodiacal light), whereas the reality of the excess is supported by the interpretation of the angular fluctuations, the origin of this component remains very puzzling. We briefly discuss possible hints to solve the problem.

Key words: cosmology: diffuse radiation - galaxies: formation - galaxies: high-redshift

1 INTRODUCTION

Recent measurements of the Near Infrared Background (NIRB) (see Hauser & Dwek 2001 for a review) have shown an intensity excess with respect to observed light from galaxies in deep field surveys (Madau & Pozzetti 2000; Totani et al. 2001). The discrepancy is maximal at 1.4 μm, corresponding to $17 - 48$ nW m^{-2} sr^{-1} (about 2-5 times the known galaxy contribution)(Matsumoto et al. 2005); significative discrepancies are found also at longer wavelengths. The large uncertainty on the amplitude of the excess is due to the subtraction of the zodiacal light (i.e. sunlight scattered by the interplanetary dust) contribution. Two different models for the zodiacal light have been so far proposed, which predict a higher (Wright 1998), or a lower (Kelsall et al. 1998) contribution of this component to he NIRB. It has to be noted, though, that the excess cannot be completely explained by a combination of galaxy and zodiacal light alone, unless current zodiacal light models are seriously incorrect.

Estimates based on theoretical models suggest that the most likely origin of such excess is redshifted light from early, very massive ($M > 100 M_\odot$) PopIII stars (Santos, Bromm & Kamionkowski 2002; Salvaterra & Ferrara 2003 [SF]; Fernandez & Komatsu 2005) if these form efficiently down to $z \approx 8$. The same stars can also account for the observed small scale angular fluctuations detected in the same bands (Magliocchetti, Salvaterra & Ferrara 2003; Kashlinsky et al. 2004; Cooray et al. 2004). In this paper, we review this conclusion in the light of the new *Spitzer* satellite and ground-based ultra deep searches for high redshift galaxies. Throughout the paper we use the AB magnitude system[⋆].

2 BASIC EQUATIONS

The mean specific background intensity, $J(\nu_0, z_0)$, at redshift z_0 observed at frequency ν_0, produced by a population of sources (in our case, the PopIII stellar clusters) characterized by a comoving emissivity $\epsilon_\nu(z)$, can be written as

$$J(\nu_0, z_0) = \frac{(1+z_0)^3}{4\pi} \int_{z_0}^{\infty} \epsilon_\nu(z) e^{-\tau_{eff}(\nu_0, z_0, z)} \frac{dl}{dz} dz, \qquad (1)$$

where $\nu = \nu_0(1+z)/(1+z_0)$, dl/dz is the proper line element, τ_{eff} is the IGM effective optical depth at ν_0 between redshift z_0 and z (see Sect. 2.2 of SF for a full description of the IGM modelling).

The source term ϵ_ν can be written, in general, as a convolution of the light curve of the stellar cluster $l_\nu(t)$ with the source formation rate (per unit comoving volume). Under the approximation that the source formation rate is constant over the source lifetime τ_{lf}, and considering the average specific luminosity per unit mass, $\bar{l}_\nu$, over such timescale, the emissivity is given by

$$\epsilon_\nu(z) \simeq \bar{l}_\nu \tau_{lf} f_\star \frac{\Omega_b}{\Omega_m} \frac{d}{dt} \int_{M_{min}(z)}^{\infty} \frac{dn}{dM_h}(M_h, z) M_h dM_h, \qquad (2)$$

[⋆] AB magnitudes are defined as AB$= -2.5 \log(F_{\nu_0}) - 48.6$, where F_{ν_0} is the spectral energy density within a given passband in units of erg s^{-1} cm^{-2} Hz^{-1}

where $n(M_h, z)$ is the comoving number density of halos of mass M_h at redshift z given by Press & Schechter (1974). The integral represents the collapsed mass per comoving volume contained in dark matter halos with mass above $M_{min}(z)$. We consider two different threshold masses depending on the relevant cooling agents: (i) atomic hydrogen (i.e. $T_{vir} > 10^4$ K); and (ii) molecular hydrogen as computed by Fuller & Couchman (2000; hereafter FC). The time derivative converts the collapse mass per comoving volume into a formation rate and the pre-factor $f_\star (\Omega_b/\Omega_m)^\dagger$ converts from total mass to stellar mass; $f_\star$ is the PopIII star formation efficiency.

As for PopIII stars properties, we adopt the light curves of massive metal-free stars (Schaerer 2002), including nebular emission and Lyα emission line (Loeb & Rybicki 1999; for a detailed discussion, see SF). For simplicity, we consider a δ−function IMF peaked at 300 $M_\odot$, since PopIII specific spectra above $M_\star > 100 M_\odot$ are essentially identical (Bromm, Kudritzki & Loeb 2001). Stellar lifetimes are also very similar for very massive stars, so we adopt a single value $\tau_{lf} = 2$ Myr.

The average flux $F_{\nu_0}(z, M_h)$ from PopIII stellar cluster of mass M_{cl} at redshift z is given by

$$F_{\nu_0} = \frac{M_{cl}}{4\pi \Delta \nu_0 \, d_L(z)^2} \int_{\nu_{min}}^{\nu_{max}} \bar{l}_\nu e^{-\tau_{eff}(\nu_0, z_0, z)} d\nu, \qquad (3)$$

where $d_L(z)$ is the luminosity distance, $\Delta \nu_0$ is the instrumental bandwidth, and ν_{min}, ν_{max} are the restframe frequencies corresponding to the observed ones. In Fig. 1 we show the expected flux from a PopIII stellar cluster with $M_{cl} = 10^6 \ M_\odot$ at redshift $z_s = 10$. It is interesting to note that such an object could be luminous enough to be detected at the NICMOS $H_{160} = 28$ limiting magnitude.

Eqs. (1)-(2) allow us to compute the diffuse NIRB background due to PopIII stars and compare it with the data. In order to determine the minimum requirements for the sources responsible for the NIR light, we consider the maximal contribution of both "normal" deep field galaxies (Madau & Pozzetti 2000; Totani et al. 2001) and zodiacal light (Wright 1998). We then determine the minimum star formation efficiency, $f_\star^m$, necessary to fit the NIRB spectrum (additionally, we assume that PopIII stars do not form below $z_{end} \approx 8$, as implied by the background spectrum J-band peak). We use here the data obtained by DIRBE and the recent determination by IRST (Matsumoto et al. 2005) that provide important information on the shape of the NIRB in the 1.4-4 μm wavelength range, rescaled using the Wright (1998) zodiacal light model subtraction. We will refer to this solution as the *minimal* NIRB model, for which $f_\star^m = 0.8$ (0.4) for H-cooling (H$_2$-cooling) halos. Note that this value is larger than derived by SF, due to their simplifying assumption that τ_{lf} is of the order of the Hubble time. Finally, for the given value of $f_\star^m$, we compute the surface density of PopIII stellar clusters required to fit the *minimal* model in the flux range F_{ν_0} and $F_{\nu_0} + dF_{\nu_0}$ as

Figure 1. Observed flux from a $M_{cl} = 10^6 \ M_\odot$ PopIII stellar cluster at $z_s = 10$. The lines show the total flux (solid), and the stellar (dotted), nebular (dashed), and Lyα line (long-dashed) contributions.

$$\frac{dN}{d\Omega dF_{\nu_0}}(F_{\nu_0}, z_{end}) = \int_{z_{end}}^{\infty} \left(\frac{dV_c}{dz d\Omega} \right) n_c(z, F_{\nu_0}) dz, \qquad (4)$$

where $dV_c/dz d\Omega$ is the comoving volume element per unit redshift per unit solid angle, $n_c(z, F_{\nu_0})$ is the comoving number of objects at redshift z with observed flux in $[F_{\nu_0}, F_{\nu_0} + dF_{\nu_0}]$, given by

$$n_c(z, F_{\nu_0}) \simeq \frac{dM_h}{dF_{\nu_0}}(z, F_{\nu_0}) \tau_{lf} \frac{d^2 n}{dM_h dt}(M_h, z). \qquad (5)$$

3 OBSERVATIONAL CONSTRAINTS

3.1 Spitzer number counts

Ground-based mid-infrared (MIR) galaxy counts are limited by the high thermal background emission and narrow atmospheric transmission window. The InfraRed Array Camera (IRAC) instrument on the *Spitzer Space Telescope* provided the first source counts in the wavelength range $3 < \lambda_0 < 10 \ \mu$m. Thanks to the low background available in space, IRAC can reach faint limiting fluxes in modest exposure times. Fazio et al. (2004b) reported the combined data from three survey fields of complementary area and depth at four IRAC wavelengths, 3.6, 4.5, 5.8, and 8.0 μm, respectively. The 3.5 and 4.5 μm images are affected by source confusion at their faint limits; for this reason, Fazio et al. (2004b) choose to truncate the source counts at the relatively bright flux value of 1.7μJy‡. After star subtraction and completeness correction, Fazio et al. (2004b) provided

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† We adopt the 'concordance' model values for the cosmological parameters: $h = 0.7$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.038$, $\sigma_8 = 0.9$, and $\Gamma = 0.21$.
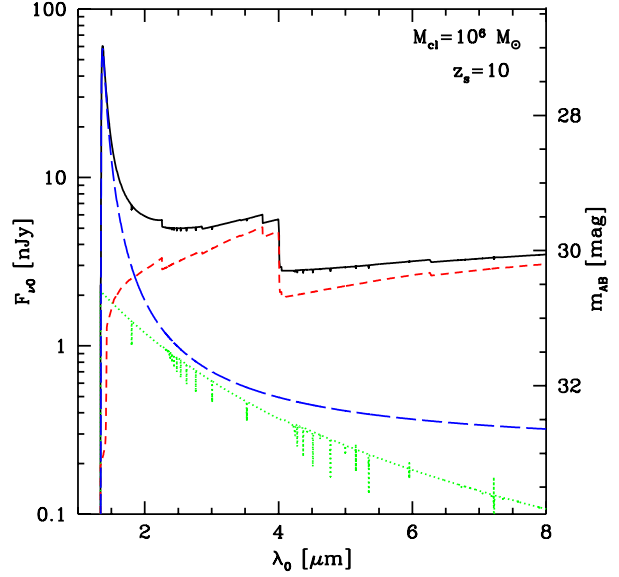
‡ In the original paper of Fazio et al. (2004b) data are given in instrumental magnitude relative to Vega. Throughout the paper we convert these into fluxes for clarity. The flux density of Vega
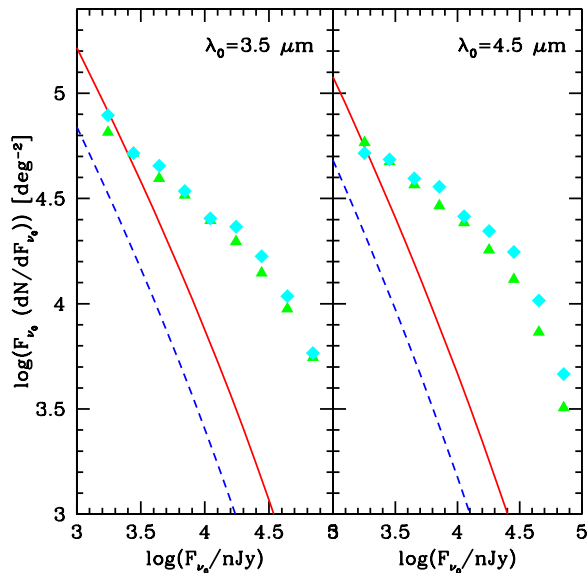
Figure 2. Expected number counts for PopIII sources fitting the NIRB excess. The solid (dashed) line refers to H-cooling (H$_2$-cooling) halos. *Left panel:* $\lambda = 3.5$ μm, *right panel:* $\lambda = 4.5$ μm. Data (Fazio et al. 2004b) points are from the *Spitzer* QSO HS1700+6416 field (diamonds) and the Extended Groth Strip (triangles).
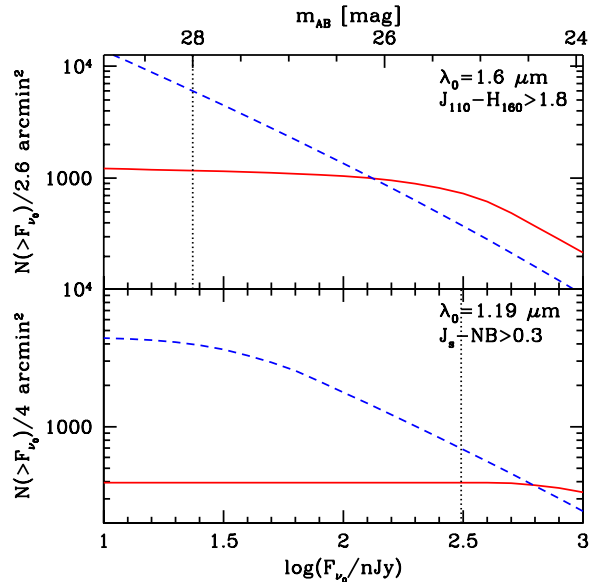

Figure 3. *Top panel*: number of $z \sim 10$ sources predicted by the *minimal* NIRB model. The selection criterion $J_{110} - H_{160} > 1.8$ has been applied and a FOV of 2.6 arcmin^2 has been assumed for comparison with NICMOS UDFs. The dotted line shows the conservative flux limit for the NICMOS survey of Bouwens et al. (2005). *Bottom panel*: number of sources with strong Lyα line emission predicted by the *minimal* NIRB model. The selection criterion $J_s - NB \geq 0.3$ has been applied and a FOV view of 4 arcmin^2 has been assumed. The dotted line shows the flux limit of the VLT/ISAAC survey of Willis & Courbin (2005). In both panels the solid (dashed) line refers to H-cooling (H$_2$-cooling) halos. Counts flatten below a certain flux as the threshold mass is reached.

extragalactic source counts for the three fields and the four IRAC wavelengths. The data for the 3.5 and 4.5 μm images are shown in Fig. 2 for the two deepest fields, around the QSO HS1700+6416 and in the Extended Groth Strip. Data the (widest) field in the Bootes region are not displayed due to their higher flux limits.

3.2 High redshift galaxy searches

The detection of galaxies at the highest redshifts is challenging because of the redshifting of UV light into the infrared and the well-known limitations of current IR instruments. In spite of this difficulties, the search for high redshift galaxies, based on the dropout technique, has provided the first tentative detection of galaxies at redshifts beyond $z \approx 7$ (Bouwens et al. 2004), stimulating a re-analysis of the small amount of deep IR data.

Bouwens et al. (2005) looked at the prevalence of galaxies at $z \approx 8 - 12$ by applying the dropout technique to the wide variety of deep F110W- and F160W-band (hereafter J_{110} and H_{160}, respectively) fields that have been imaged with the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). The principal data set is constituted by two 1.3 arcmin^2 deep NICMOS parallels taken with the Advanced Camera for Surveys (ACS) Hubble Ultra Deep Field (UDF; each has about 160 orbits data). Complementary shallower fields possessing similar $J_{110} + H_{160}$ imaging are analysed as well. The 5σ limiting magnitude for the UDFs is ≈ 28.6 in J_{110} and ≈ 28.5 in H_{160} (0″.6 aperture). Since

in the 3.5 μm (4.5 μm) IRAC bandpass is 277.5 (179.5) Jy (Fazio et al. 2004a).

these limiting magnitudes are reached only in the deepest regions of the two NICMOS UDFs, we adopted the conservative limiting magnitude $H_{160} = 28$ (Bouwens, private communication). The primary selection criterion for high-z sources is $J_{110} - H_{160} > 1.8$. Using this criterion, Bouwens et al. (2005) found eleven sources. Eight of these are ruled out as credible $z \simeq 10$ sources, either as a result of detection ($> 2\sigma$) blueward of J_{110} or because of their colors redward of the break ($H_{160} - K \approx 1.5$). The nature of the three remaining sources could not be assessed from the data, but this number appears consistent with the expected contamination from low-redshift interlopers. Hence, Bouwens et al. (2005) concluded that the actual number of $z \simeq 10$ sources in the NICMOS parallel fields must be three or fewer.

Willis & Courbin (2005) have presented a deep, narrow J-band search (called ZEN) for protogalactic Lyα emission at redshift $z \approx 9$, combining a very deep VLT/ISAAC image of the Hubble Deep Field South using a narrow-band (hereafter NB) filter centered at 1.187 μm, with existing deep, broad-band images covering optical and NIR wavelengths. They searched for $z \approx 9$ Lyα-emitting galaxies displaying a significant narrow-band excess relative to the J_s band (i.e. $J_s - NB \geq 0.3$) that are undetected at optical wavelengths. They identified no sources, matching these requirements, up to a NB magnitude limit of 25.2 in a field of ~ 4 arcmin^2.

4   IMPLICATIONS FOR NIRB MODELS

Having fixed the *minimal* NIRB model (see Sec. 2), we ask what are the predictions of such model in terms of: (i) number counts in the 3.5 and 4.5 μm *Spitzer* bands, (ii) number of *J*-dropouts that can be detected with NICMOS, and (iii) number of strong Lyα-emitting galaxies identifications.

The main results are shown in Figs. 2-3 for the two cases of H- or H$_2$-cooling halos. In Fig. 2 we plot the predicted differential number counts compared to *Spitzer* data; Fig. 3 shows the total number of *J*-dropouts expected in the NICMOS ultra deep observations (top panel) and in the ZEN search (bottom panel).

If the NIRB excess is to be ascribed to PopIII clusters, we find that even for the *minimal* NIRB model a substantial fraction of the *Spitzer* number counts is provided by such galaxies, particularly at the faintest fluxes. For $T_{vir} > 10^4$ K halos, almost all the (3.5 μm and 4.5 μm) IRAC counts at the flux limit of the survey should correspond to PopIII galaxies, whereas for H$_2$ cooling halos $\approx 50\%$ of the observed sources at 1.7 μJy should lie at $z > 8$. Even at fluxes of 4.4 μJy, where confusion noise and completeness problems are less important, $\approx 60\%$ (20%) of the detected *Spitzer* sources should be PopIII galaxies in H-cooling (H$_2$ cooling) halos.

The situation becomes even more serious if we consider the predictions for the number of $z \approx 10$ PopIII galaxies detectable in the NICMOS UDFs. Adopting the same selection criterion $J_{110} - H_{160} > 1.8$ as in Bouwens et al. (2005), the model predicts that thousands of these sources should be detected. More precisely, 1165 (5634) *J*-dropouts should be observed for H-cooling (H$_2$ cooling) halos below the conservative magnitude limit $H_{160} = 28$. These numbers are at odd with the mere 3 (tentative) detections reported by Bouwens et al. (2005).

The *J*-band peak in the NIRB excess has been interpreted (SF; Santos et al. 2002) as due to strong asymmetric Lyα emission line from PopIII clusters at $z \approx 9$. Such sources can be identified in a narrow *J*-band survey from a significant narrow-band (NB) excess relative to the flux observed in a broader *J*-band. In the bottom panel of Fig. 3 we show that, by applying the criterion $J_s - NB \geq 0.3$, almost 394 (683) H-cooling (H$_2$-cooling) sources should be identified up to a magnitude limit $NB = 25.2$ in a 4 arcmin^2 field for the *minimal* NIRB model. Instead, the ZEN search implementing the same selection criterion has yielded no identification.

Can we reconcile the NIRB-PopIII interpretation with the constrain given by the currently available observational data ? The *Spitzer* number counts can be reduced by quenching the formation of PopIII stars in larger halos as a result of the transition to a PopII mode driven by chemical feedback (Schneider et al. 2002, 2003, 2005). In this case the *minimal* NIRB model is reproduced if PopIII star formation occurs in all halos with masses in the range $M_{min}(FC) < M_h \lesssim 10^9 M_\odot$ with $f_\star^m = 0.8$. Chemical feedback would drastically reduce the number of PopIII IRAC galaxies without reducing the NIRB intensity, the latter being mainly sustained by smaller halos. This solution, unfortunately, does not solve the problem with the NICMOS fields and the narrow *J*-band search. The reason is well exemplified in Fig. 1, where we show that at $z \approx 10$, for the expected Lyα fluxes, NICMOS would be able to detect stellar masses

as small as $M_\star = 2 \times 10^5 M_\odot$, or $M_h \approx 2 \times 10^6 M_\odot$. This figure is increased to $M_h \approx 5 \times 10^7 M_\odot$ for VLT/ISAAC. Hence chemical feedback cannot provide a way out.

We can compute a strong limit on the fraction of NIRB light produced by PopIII stars based on the three candidate $z = 10$ galaxies in the UDFs.

Even if all candidates turn out to be genuine $z = 10$ PopIII galaxies, the contribution to the NIRB is less than 0.05(0.04) nW m^{-2} sr^{-1} in the J (H) band, i.e. $\approx 1/340$ of the minimum observed NIRB excess. Within these limits, the predicted contribution to *Spitzer* counts at larger wavelengths is completely negligible and no sources should be present in the ZEN search.

Alternatively, if PopIII ionizing photons largely escape from star forming environments, the Lyα line could be produced in the intergalactic medium. The consequent strong surface brightness decrease would prevent detection and association with the parent galaxy; however, these Lyα photons would still contribute to the NIRB. This scenario offers a possible explanation for the null ZEN result. However, the stellar (as opposed to nebular) emission would make $z \approx 10$ PopIII clusters observable as *J*-dropouts even in this case. The three NICMOS candidates (corresponding to $f_\star^m = 1.5\%$) imply then a small NIRB contribution from PopIII, amounting only to 1/24 of the minimum observed excess. Again, these sources would be below detectability for *Spitzer* at larger wavelengths.

In conclusion, we find that if the NIRB excess is made entirely by high redshift PopIII clusters, these should have already been observed in deep galaxy searches in large numbers. The few (possibly none!) detections of such objects offers little room for the PopIII explanation of the NIRB excess, leaving us with a puzzling question concerning the origin of this mysterious background component.

5   DISCUSSION

Recent measurements of the diffuse background light in the NIR bands have shown an intensity excess with respect to the light produced by known galaxies in deep field surveys. Theoretical models have suggested that this excess could be produced by redshifted light from the first very massive ($M > 100\ M_\odot$) PopIII stars (Santos et al. 2002; SF) if these form efficiently down to $z \approx 8$. The same stars can also account for the observed small scale angular fluctuations detected in the same bands (Magliocchetti et al. 2003). We have reanalysed this conclusion in the light of new *Spitzer* MIR observations, and recent high-z galaxy searches.

Our main result is that any model reproducing the minimum value of the excess with emission from PopIII clusters, inevitably predicts that a large fraction (in some case all) of IRAC (3.5 μm and 4.5 μm) counts at the faintest fluxes is due to galaxies at $z > 8$. Even more seriously, the same models overpredict the number of *J*-dropouts and Lyα emitters identified in deep field searches by a factor of thousands. In particular, the interpretation of the background light *J*-band peak as due to redshifted Lyα emission from sources at $z \approx 9$ would imply a large number (394/683 depending on the main gas cooling agent) of identifications in narrow *J*-band surveys. Instead, no such sources have been detected by the ZEN search.

The three NICMOS $z \approx 10$ candidate PopIII galaxies limit the contribution of such sources to the NIRB excess to be $\leq 1/340$. This constraint is somewhat looser if the Lyα emission originates in the IGM rather than in the star forming nebula. In this case the NIRB excess fraction due to PopIII clusters is $\leq 1/24$.

As we are facing such a severe problem, it is wise to consider possible NIRB data contaminations from spurious components. The largest experimental uncertainty is represented by zodiacal light subtraction. Although it is in principle possible to explain the excess in the NIRB with zodiacal light, this might imply a revision of the properties of dust grains canonically assumed (Dwek, Arendt & Krennich 2005). On the other hand, the existence of the NIR excess above the contribution of deep field galaxies at $z < 5$ seems to be suggested by the analysis of the TeV spectral features of distant blazars revealed by Cherenkov experiments (although different interpretations cannot be excluded, see Aharonian et al. 2005). Finally, zodiacal light has been excluded as a possible source of the observed NIRB angular fluctuations (Kashlinsky et al. 2002, 2005).

The interpretation of the NIRB excess must then be different. Are there viable alternatives ? Cooray & Yoshida (2004) have speculated that a fraction of the unresolved NIRB can be due to high-z miniquasars. However, this hypothesis can be readily discarded by noting that emission from a population of early miniquasars significantly contributing to the NIRB, largely exceeds the unresolved fraction of the Soft X-ray Background (Salvaterra, Haardt & Ferrara 2005; Madau & Silk 2005). In particular, Salvaterra et al. (2005) have shown that the SXRB constrains the contribution of these sources to be $\leq 10^{-3}$ nW m^{-2} sr^{-1}. High redshift supernovae have also been examined by Cooray & Yoshida (2004), who exclude any significant NIRB contribution from such objects. Finally, more exotic sources as sterile neutrinos have been firmly excluded as viable explanations for the excess by Mapelli & Ferrara (2005).

What are the remaining possibilities ? Local, low surface brightness galaxies undetected by available instruments might reduce the gap between NIRB data and the integrated light of deep field galaxies; similarly the light from the outer regions of moderate redshift galaxies could be missed (Bernstein, Freedman & Madore 2002). Although the nature and properties of such unidentified objects are unknown (note that these sources must have $J > 29$), these local galaxies would not explain the excess in the small angular scale fluctuation observed in the NIRB in the J band (Kashlinsky et al. 2002). A more promising alternative would be to locate these faint sources at $z \approx 2 - 3$, for example if the Lyman Break Galaxies luminosity function is extremely steep.

In any case a considerable amount of study will be necessary to fully understand the puzzling nature of the NIRB excess.

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